

20201214 PAIMAN

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Submission date: 14-Dec-2020 09:12AM (UTC+0700)

Submission ID: 1474158202

File name: 10._Recent_Development_of_Weed_Artikel.pdf (769.92K)

Word count: 6940

Character count: 37615

Recent Developments of Weed Management in Rice Fields

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ABSTRACT

Rice is an important source of food worldwide. However, the growth of weeds in paddy fields pose a major biological threat to higher rice productivity and quality. Various cultural, chemical, biological, and physical practices affect the growth and composition of weeds in paddy fields. In general, weeds can be effectively controlled through herbicides although the use of chemical-based weed control measures do not provide sustainable solution for the long term. This review highlights the different weed types and their effects on rice production as well as weed management methods that can be used to control the growth of weeds in rice fields. The major points are as follows: (1) there are several types of weeds found in rice (i.e., grassy, sedges and broad leaf), (2) weeds contribute to the rice crop losses and (3) there are a few methods applied for weed control. This review has found that it was beneficial to use biological method instead of using herbicide to control the weeds. This paper can contribute to the knowledge for increasing crop production and sustainable weed management.

Keywords

rice, rice field, rice productivity, weed control, weed management, weeds

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1. Introduction

Rice (*Oryza sativa* L.) is an essential food in Asia and the Pacific, with more 90 % of the rice in the world being produced and eat up within the Asia-Pacific area (Chauhan and Johnson, 2011; Chauhan, 2013; Chauhan and Abugho, 2013; Nadir *et al.* 2017). Due to the increasing prosperity and rates of urbanization, rice consumption per capita has been gradually declining in the middle and high-income populations in Asian countries such as Korea and Japan. However, approximately one-fourth of the Asian population consists of low income earners and hence, there will be a significant unmet demand for rice in the near future as rice consumption will increase in these countries. At present, the population in Asia is growing at a rate of 1.8 % per year and it is thought that the population number may continue to increase up to the middle-half of the next century. The growth projection for the world's population indicates that there will be an average increase of 51 % by 2025 and up to 87 % in some cases over the base year of 1995 (Papademosiou, 2000). Similarly, Venkatesh (2016) also reported that the rice is regarded as the 'life line' in many countries of the Asia-Pacific region, with over 90 % of the world's rice accounting for 56 % of humanity, manufacturing and many more. Hence, the demand for rice consumption is predicted to increase more quickly than its production in most of the countries. Besides that, the continuous and large quantity of water supply is important for rice production. However, irregular rainfall caused the lacking of water resources worldwide (Simm *et al.*, 2017).

Received November 4, 2020, Revised November 22, 2020, Accepted November 22, 2020

Published online: December 13, 2020. *Correspondence to P.: paiman@upy.ac.id

In Indonesia, rice production is an important sector of the nation's economy. It is the 3rd largest producer of rice globally. Moreover, rice has always been a staple food for most Indonesians, whereby it represents the greater part of the whole calories in their average diet and it represented a source of livelihood for approximately 20 million households, or roughly 100 million people during the late 1980s. Rice cultivation in Indonesia accounted for approximately 10 million hectares of land throughout the archipelago, mainly on cultivation lands known as 'sawah'. The supply and effective control of the water system are crucial in rice cultivation, especially when planting high-yield seed varieties. For instance, the irrigated 'sawah' covered up to 58 % of the total cultivated area in 1987, while rain-fed 'sawah' accounted for 20 %, and lading, also known as dry land cultivation, together with swamp land or tidal cultivation accounted for the remaining 22 % of rice cropland (Venkatesh, 2016).

To date, rice is still the most important food crop across Indonesia, providing approximately 50 % of the daily caloric requirements. It was estimated that in 2017, the average Indonesian consumed approximately 114.6 kg of rice in 2017, thus accounting for the total rice consumption reaching up to 33.5 m tons in that year alone. With the increasing use of modern planting techniques as well as improved infrastructure and the implementation of new regulations, the country continues to promote self-sufficiency in rice production as a major policy. Apart from increasing the national production for rice, this self-sufficiency program also aims to minimize rice imports and stabilize the domestic prices and reserve rice stock. Hence, President Joko Widodo and his administration have pushed for major investments, particularly in irrigation infrastructure, with 781 km of irrigation channels developed in 2018. Besides, the government has pledged to build more irrigation structures since only 11 % of rice paddy fields, or approximately 780,000 ha, were watered by existing dams in early 2019 and this figure is expected to increase to 20 % upon the construction of 58 additional dams (Anonymous, 2020).

Weeds have been around throughout ancient times and are defined as non-crop plants or unwanted plants growing in the same field as the crop plants. Weeds do not only grow together with the main crops but they also compete with the main crop plant for basic necessities such as food, sunlight, space, nutrients and many more and result in the significant loss in agricultural production (Das, 2008). Besides, Monaco *et al.* (2002) described weeds as plants that grow in places where they are unwanted and are considered as undesirable plants. In most cases, weeds take advantage of sites that are disturbed sites and have characteristics that enable them to utilize the available resources efficiently and thus, grow abundantly.

It is evident that the excessive use of chemicals to control the weed population has adverse effects on human health and the global environment (Adhikari *et al.*, 2019). It was recently reported that in dry-seeded rice (DSR) systems, the simultaneous growth of rice seedlings and weeds under the alternate wet and dry field conditions favored a high weed infestation (Awan *et al.*, 2019). In a study by Sugimoto *et al.* (2019), the authors observed an increasing number of jellyfish in the waters surrounding Japan during the recent years and indicated that this observation had a negative effect on the environment and caused serious damage to the coastal areas and fisheries. The authors also developed a bioherbicide derived from jellyfish chips (desalted, dried, or shredded jellyfish), that not only acts as an organic fertilizer but also as a bioherbicide that could be used in the paddy fields. On the other hand, another study by Paiman *et al.* (2020) observed that soil tillage could cause the germination of weed propagules and thus be used to control soil solarization prior to germination. Nevertheless, weeds have become a major challenge in rice production due to the shift in cultural practices in the paddy fields (Karim *et al.*, 2004). A small number of studies have investigated the negative effects of weeds that ultimately lead to reduced productivity of rice. Hence, this study aims to analyze the current weed management procedures in paddy fields to minimize the negative consequences of weeds.

2. Types of weeds found in rice fields

Monaco *et al.* (2002) previously defined a weed as a plant that grows where it is unwanted, or a plant that is out of place. Weeds are classified as pests, together with insects, nematodes, plant diseases, and rodents. Chemicals that are used to control a pest are known as pesticides while herbicides are chemicals that are used specifically for weed control. Weeds have many variable characteristics compared to the crop for examples lack of seed dormancy, uniform growth and high yields. Thus, weeds tend to show larger potential capacity to adapt to stress (e.g., climate change) than crop plants (Korres *et al.*, 2016).

Weedy rice shows to the undesirable plants of the family *Oryza* which have certain unwanted agronomic characteristic and represent a significant hazard to continuous global rice production. Weedy rice or called as "red rice" consolidates all unfortunate weedy population of the genus *Oryza* developing in and over paddy fields (Nadir *et al.*, 2017). Tang and Morishima (1997) stated that weedy rice or *Oryza sativa* f. spontanea is taxonomically delegated indistinguishable species from planted rice. Weedy rice spreads widely across the globe. Zhang *et al.* (2014) revealed solid genetic separation for Asian weedy rice comprising of indica, japonica, and a common type depend on geographical distribution designs.

The weed flora population in direct seeded rice (DSR) typically consists of various types of grasses, sedges and broad-leaf weeds (Table 1). The community composition of these weed types varies based on several factors which include the crop establishment methods and cultural methods used, crop rotation, location, water and soil management, weed control methods, climatic conditions, and existing weed flora population in the area. To date, *Echinochloa colona* and *E. crus-galli* are the most notorious weeds affecting the DSR system (Nagargade *et al.*, 2018).

Vincent (2016) investigated the diversity of weeds in the paddy fields of the Kirinyaga County in Kenya. The study was performed in the Mwea Irrigation Scheme, the largest public irrigation settlement situated in Kenya. Among the broad-leaf weed species that were sampled, *Ludwigia adscendens* L., *Marsilea minuta* L., and *Spharanthus cyakuloides* were the most abundant species, accounting for 97 %, 94 %, and 84 %, respectively. The least abundant species in this category of weed species was the presence of *Eclipta prostrate* L. (16 %) in the Scheme. It is also important to note that only four species were present below 50%, which included *Monochoria vaginalis* Burm.f (23 %), *Ammania coccinea* Rottb. (39 %), *Sphaeranthusafricanus* (32 %) and *Eclipta prostrata* L. (16 %). The results from the grass species indicated that *Leptochloa chinensis* L. was the most abundant (97 %), while *Echinochloa crusgalli* L. (77 %) had the least abundance. The most interesting aspect of the grass species was that all four species were relatively abundant with more than 71 % as compared with the grasses and sedges, respectively. The species frequency for the sedge species were relatively lower than those of the broadleaf and grass species, accounting for less than 33 %. The *Cyperus difformis* L. species was the most abundant (33 %), while *Cyperus rotundus* L had the least score. In addition, Becker and Johnson, (2001), investigated the weeds in upland rice, West Africa. The principal weed species in upland rice were stated in the Table 2. Based on Table 2, *Chromolaena odorata* dominated the cultivated area in the forest zone.

Table 1: Weeds found in direct seeded rice reported by Nagargade *et al.* (2018)

Type of weeds	Name
Grassy weeds	<i>Digitaria setigera</i> , <i>Echinochloa crus-galli</i> , <i>Eleusine indica</i> , <i>Ischaemum rugosum</i> , <i>Leptochloa chinensis</i> , <i>Oryza sativa</i> (weedy rice), <i>Paspalum distichum</i>
Sedge	<i>Cyperus iria</i> , <i>Cyperus difformis</i> , <i>Cyperus rotundus</i>
Broad leaf weeds	<i>Commelina benghalensis</i> , <i>Caesulia axillaris</i> , <i>Eclipta prostrata</i> , <i>Ipomoea aquatica</i> , <i>Ludwigia octovalvis</i> , <i>Ludwigia adscendens</i> , <i>Monochoria vaginalis</i> , <i>Sphenoclea zeylanica</i>

Table 2: The weed species in upland rice at four agroecological zones (Becker and Johnson, 2001)

Agroecological Zone	Weed species
Guinea savanna	<i>Andropogon</i> spp., <i>Pennisetum polystachion</i> , <i>Paspalum scrobiculatum</i> , <i>Rottboellia cochinchinensis</i> , Woody regrowth, <i>Hackelochloa granularis</i> , <i>Ipomoea</i> spp., <i>Spermacoce</i> spp., <i>Celosia trigyna</i> , <i>Digitaria</i> spp., <i>Aspilia bussei</i>
Derived savanna	<i>Imperata cylindrica</i> , <i>Andropogon gayanus</i> , Woody regrowth, <i>Commelina benghalensis</i> , <i>Digitaria horizontalis</i> , <i>Paspalum scrobiculatum</i> , <i>Rottboellia cochinchinensis</i> , <i>Hackelochloa granularis</i> , <i>Spermacoce ruelliae</i> , <i>Ageratum conyzoides</i>
Bimodal forest	<i>Chromolaena odorata</i> , Woody regrowth, <i>Triumfetta</i> spp., <i>Rottboellia cochinchinensis</i> , <i>Momordica charantia</i> , <i>Physalis angulate</i> , <i>Mariscus cylindristachyus</i> , <i>Scleria</i> spp., <i>Panicum laxum</i> , <i>Sorghum arundinaceum</i> , <i>Paspalum scrobiculatum</i> laxum, <i>Sorghum arundinaceum</i> , <i>Paspalum scrobiculatum</i>
Monomodal forest	<i>Chromolaena odorata</i> , <i>Ipomoea</i> spp., <i>Triumfetta</i> spp., <i>Calopogonium mucunoides</i> , <i>Mariscus cylindristachyus</i> , <i>Crotton hirsutus</i> , Woody regrowth, <i>Sida</i> spp., <i>Physalis</i> spp., <i>Paspalum scrobiculatum</i> , <i>Cynodon dactylon</i>

3. Effects of weeds on rice

A single weed in one life cycle can produce a high amount of propagule dispersions to the soil, whereby many of these seeds may germinate while others remain dormant for an extended period. Weed seeds usually infest the soil in cropland areas million per acre. The term, dormancy, refers to an internal characteristic of the seed that inhibits its germination under unfavorable hydric, thermal, and gaseous conditions. Some weed seeds are deeply buried in the soil, while others lie on the surface or in the litter layer just above the soil surface. In pastures, approximately 64 to 99.6 % of all weed seeds were found in the upper 4-inch soil layers, with greater seed numbers residing in the 1 to 4-inch soil layers as compared to the surface and top 1-inch layer of soil. Various types of propagules were identified in form of the seeds, rhizomes, stolon, tubers, and bulbs (Paiman *et al.*, 2020).

Weeds cause great losses in rice yields as they compete with rice for nutrients, space, water, and light (Smith, 1983; Khanh *et al.*, 2007; Vincent, 2016). In some instances, weeds are carriers for major diseases such as rice blast disease (*Pyricularia oryzae*). It should also be mentioned that a majority of farmers use recycled seed during translocation, thus aggravating the current situation (Vincent, 2016). Weeds represent turn into extensive in rice yield due to the changes in cultural practices. For instance, direct-seeded field offer aerobic growth conditions for weed as they are not immersed in water during the first phase of plant growth and thus more useful for weed growth, particularly in areas with highly competitive grass weed populations (Moody and De Datta, 1982; Chuhan, 2012). The infestation of rice by weeds since 1990 has accentuated this problematic situation and rice yields will be definitely decrease if the weed populations are not properly managed. Consequently, effective management of weed is a vital pre-requisite notable production of rice. For instance, if crop losses of approximately 10–20 % are recovered through effective weed management with the use of appropriate herbicides, there will be additional yield of 0.3–0.6 t/ha and approximately RM 150 for 300 ha⁻¹ or US\$50 for 100 ha⁻¹ will be obtained as additional income for farmers (Karim *et al.*, 2004). In the recent decade, agricultural handling, for example direct seeding, together with the mutual utilization of modern machinery, have led to the fast growth of weedy rice over several rice fields in Malaysia (Sudianto *et al.*, 2016).

On the other hand, herbicides such as Dalapon have been extensively used for weed management in agricultural practices. Halogenated hydrocarbons are commonly found in the environment due to their excessive use in various industries including the agriculture sector as insecticides, herbicides, solvents, and intermediates for chemical syntheses. Halogenated compounds are toxic and persistent in the environment, thus causing environmental pollution and human health problems (Ismail *et al.*, 2018a, b). Moreover, the herbicides can accumulate in the soil, then become mobile due to rain and irrigation practices. Eventually, it will move to the river and sea (Ismail *et al.*, 2017). More importantly, it has been noted that the overwhelming dependence on these chemicals to manage the weeds population in sector of agricultural can result in everlasting unfavorable impacts on the current environment (Ismail *et al.*, 2016). In addition, the pesticide residues from agriculture sector which contaminated the food or water lead to the illness of people who consume it (Rueda-Ayala *et al.*, 2020). The feature of water and soil contamination due to pesticide residue also documented (Schwarzenbach *et al.*, 2010; Morrissey *et al.*, 2015; Yadav *et al.*, 2015).

It is estimated that weeds contribute to approximately 9 % of rice crop losses worldwide (Rodenburg and Johnson, 2009), with decreases of 94 % to 96 % in rice paddies in the Philippines (Chauhan and Johnson, 2011) and losses of 30 % to 73 % in Colombia (Cobb and Reade, 2010). Therefore, appropriate control and management methods in rice crops are vital to minimize the negative effects of weeds.

4. Methods of weed control

Weeds are a notorious pest in rice crop production that can be managed effectively by controlling the spread of weeds. The convenient management strategies are needed to reduced yield lost and preserve the rice production since the weeds of rice especially weedy rice is very challenging to control. Hence, integrated control measures comprise of indirect control (*e.g.*; the use of clean, weed-free seeds, tilling and land preparation, water management, choice of cultivar, and crop rotation) and direct control methods (*e.g.*; manual weeding and chemical applications) have been enforced (Azmi *et al.*, 2000). The methods used to control weeds have been widely investigated in several studies and are summarized in Table 3.

Paiman *et al.* (2020) investigated the use of soil solarization in Yogyakarta, Indonesia to control the weed propagules. Weeds grow from the reserves of weed propagules in the soil. Hence, in this study, the authors sought to understand the effects of soil solarization on weed propagules in the soil. A survey was conducted to select land

that ¹⁵ is overgrown by a homogenous weed species. The statistical design of the study consisted of two factors and the experimental units were arranged in the randomized complete block design (RCBD) with three replications. The differences between the average mean values of the treatment groups were compared using DMRT at a significant level of 0.05. The first factor was based on the colored polyethylene (PE) films which consisted of three levels, namely black, red, and transparent. The second factor was the duration of soil solarization which consisted of three levels, namely 10, 20, and 30 days. One treatment of non-solarization was performed as a control. The results of the study showed that soil solarization was able to reduce weed propagules according to the soil depth. Specifically, soil solarization effectively reduced the highest weed propagules up to 9–12 cm soil depth. Soil solarization treatment for 30 days was more common with high soil temperature. The use of transparent PE films and soil solarization for 30 days effectively reduced 77.8 % of weed propagules in 0–3 cm soil depth (Paiman *et al.*, 2020).

On the other hand, biodiversity-based farming techniques are thought to improve the efficiency and sustainability of production, with lesser adverse environmental impacts and reduced usage of external inputs. ⁸ After performing two-season experiments, Li *et al.* (2019), observed that the diversity and species richness of weed communities present in the mixed-cropping integrated with rice-duck co-culture (MCDC) system were significantly reduced as compared to those present in the mono-cropping ⁸ system. Additionally, the abundance of moths, also known as ¹⁷ rice leafrollers, in the MCDC system appeared to be significantly lower than those in the mono-cropping system (Li *et al.*, 2019).

Awan *et al.* (2019) performed experimental studies at the Rice Research Institute, in ² Lahore in 2010 and 2011 to evaluate the weed management in dry-seeded rice. In these studies, several types of weed control treatments (bispiribac sodium, bispiribac sodium + hand-weeding, ethoxysulfuron, ethoxysulfuron + hand-weeding, single hand-weeding, and double hand-weeding) were performed in a randomized complete block design also compared with weedy check treatment. The results indicated that the maximum weed control of 97.2 % and 94.5 % was attained in the double hand-weeded and bispiribac sodium + hand-weeded treatment plots, respectively, during the first year. In contrast, a maximum weed control of ^{23.3} % was achieved in bispiribac sodium + hand-weeded plots during the second year, similar to treatment plots with double hand-weeding (93.5 %) and ethoxysulfuron + hand-weeding (93.0 %). Moreover, for both the years, bispiribac sodium + hand-weeded treatment plots attained the maximum number of tillers (m^{-2}) (338 and 297) and longest panicle lengths (27 and ^{28.2} cm), in addition to producing the maximum number of grains per panicle (116.3 and 121.8). The highest (3.2–4.0 $t\ ha^{-1}$) ² paddy yield was also obtained from the bispiribac sodium + hand-weeding treatment plot, whereas the lowest (0.9–1.1 $t\ ha^{-1}$) paddy yield was observed in the non-treated plots. Thus, the results of the study indicated that the integration of the hand-weeding technique with the application of bispiribac sodium was the most effective weed management option in DSR systems to manage the weed growth also obtain higher paddy grain yields.

A recent study was also performed by ⁴ Wei *et al.* (2019) to investigate the integration of the rice-duck farming system in the paddy fields. The utilization of coupled cropping-breeding modes is highly recommended mainly due to their environmental-friendly system and sustainability. The integrated rice-duck farming method is a common ecological farming system in paddy fields that has been widely implemented in Asia, whereby significant areas of cropland has been dedicated to planting rice. The results revealed that the rice-duck farming system significantly lowered the soil seed bank density levels by more than 40 % and the turbid water treatment values during the early and late seasons of rice growth were 18.2 % and 30.5 %, respectively. Besides, the rice-duck farming method significantly changed the vertical distribution of soil seed bank through the substantial decline in seed density of the topsoil (0–5 cm). The notable alteration in soil seed bank density significantly contributed to the reduction of the above-ground weed density as a significant correlation was observed between the soil seed bank density during the

early rice growing season and the weed density during the late season. The declining levels of the soil seed bank and weed density observed in the integrated rice-duck farming method indicate the high efficiency of this system as a biological means for weed control (Wei *et al.*, 2019).

On the other hand, the combined use of jellyfish chips and rice bran as fertilizers successfully controlled the weed populations in the paddy field and provided a grain yield that was similar to that of the conventional rice cultivation method. The improvement in grain yield may be attributed to the differences in the organic fertilizer composition and the effective fertilizer onset time. Furthermore, the increase in herbicidal effects may be due to the synergistic effects of various growth-suppressing substances in these organic fertilizers. Overall, the combined application of jellyfish chips and rice bran may be utilized as an innovative organic method in rice cultivation (Sugimoto *et al.*, 2019).

In organic farming, the use of the snail, *Ampullaria tischbeini* (Dohrn), in saline paddy fields not only reduces the use of chemical fertilizers and herbicides but also greatly enhances the physical, biological, and chemical properties of the soil. This snail is able to survive in both saline and non-saline paddy fields. Laboratory and field experiments have shown that the snail is able to survive in paddy fields containing Cl^- concentrations of up to 0.15 % (saline condition). After 40 to 45 days of sowing, approximately 2600 to 3300 snails per hectare were released to the saline paddy fields, whereby the released snails not only removed almost all the weeds but also improved the chemical, biological, and physical properties of the paddy field soil. In the paddy soil, a high amount of calcium ions (Ca^{2+}) is produced due to the decomposition of shells derived from dead snails. Calcium is important for the remediation of saline soil as it displaces sodium and reduces the exchangeable percentage of sodium. In the paddy fields, the movement of snails also led to an improvement in the physical properties of soil such as porosity, texture, and water infiltration rates. Additionally, the snail excretions led to the substantial increase in soil nutrient content and organic matter. In the saline paddy fields with artificially released snails, a higher rice yield was also observed as compared to the control plot (no snails) (Jong-Song *et al.*, 2018).

In a recent study, Ratnayake *et al.* (2018) introduced an alternative technology for farmers to improve rice grain production. Experiments were done to investigate the outcome of polythene mulching on the improvement of rice production through the use of suitable soil water regimes and weed management methods. In the study, seed broadcasting and transplanting were established with and without the use of polythene mulching using the rice variety, At 362. The results showed that mulching efficiently maintained soil moisture at satisfactory levels during the dry seasons whilst reducing almost 100 % of weed growth. Furthermore, a significantly higher plant growth and grain yield were also observed with mulching as compared to the control experiment. Hence, the technology was recommended to farmers to facilitate their rice production as weed contamination was one of the major threats confronted by paddy farmers in Sri Lanka (Ratnayake *et al.*, 2018).

Muhammad *et al.* (2016) performed a study involving five different weed control methods, namely hand-weeding, inter-row tine cultivation, hoeing, inter-row spike hoeing, and herbicide treatments (Nominee 100 SC). Weeds are reportedly known as a major challenge in achieving good yields in DSR. The results of this study revealed that hand-weeding, hoeing, inter-row tine cultivation, and herbicide treatment with bispyribac sodium effectively controlled the weed population at levels of 95 %, 81 %, 71 %, and 50 %, respectively, as compared to the control (non-weed).

Besides that, Mamun (2014) has studied the modelling rice-weed competition in direct-seeded rice cultivation. A rectangular hyperbolic equation was helped for prediction of rice yield as a function of weed densities. It was found that the weeds constructed more or less double dry matter in 2009 compared to 2010. Weed dry weights expanded hyperbolically with growing of weed density.

Moreover, Khanh *et al.* (2007) noted that the use of biological methods to control weed growth alleviated the heavy reliance on synthetic agrochemicals, thus resulting in increased agriculture sustainability. The phytotoxins derived from plants exert a strong allelopathic activity that may be utilized as novel source of natural herbicides and thus, reduce the current use of synthetic herbicides and facilitate the development of biological-based pesticides. The direct application of plant agrochemicals with strong allelopathic effects to paddy field soil at 1 to 2 tons ha⁻¹ were shown to effectively suppress the growth of weeds. It is essential to note that the efficacy of allelochemicals in paddy field for weed control and management involves several processes, interactions, and physiological functions that occur in the natural environment. However, whilst many potent bioactive compounds have been isolated from plants, very few have been successfully used as bioactive herbicides. Among the derivatives that were synthesized, allelochemicals dihydro-5,6-dehydrokawain (DDK) and dimethyl phosphorothionate were shown to exert the most potent herbicidal and antifungal effects. Nevertheless, the direct application of allelochemicals in the natural environment is challenging as they are often degraded prior to reaching the targets. Hence, the synthesis of safe, bioactive pesticides from plant phytotoxins is necessary for effective weed and pest management in paddy fields (Khanh *et al.*, 2007).

Batish *et al.* (2007), studied the allelopathic potential of plant (*Tagetes minuta*) to suppress the rice weeds such as *Echinochloa crus-galli* and *Cyperus rotundus*. *Tagetes minuta* is an aromatic essential plant with broad range biological activity involve medicinal properties. The emergence and growth of both weeds were decreased after *T. minuta* leaf powder applied to the rice field. Thus, Batish *et al.* (2007) wrapped up that *T. minuta* can be used as natural herbicide because being potential to suppress the weed in rice field.

Similar study on allelopathic potential of plant was also reported previously by Lin *et al.* (2004) but they used different type of plant. Dwarf lilyturf (*Ophiopogon japonicus* Ker-Gawl), which is known as a medicinal plant for treating the sore throat was studied in controlling the weeds in rice fields. They found that Dwarf lilyturf plants can inhibit the weeds in rice fields. This finding of Lin *et al.* (2004) was consistent with Batish *et al.* (2007), showed that the allelopathic potential of plant may be a natural rice field herbicide.

Table 3: The weed species in upland rice at four agroecological zones (Becker and Johnson, 2001)

Methods of weeds control	Treatment	References
Mechanical weed control	Soil solarization	Paiman <i>et al.</i> (2020)
Biodiversity-based farming systems	Mixed-cropping with rice-duck co-culture (CDC) systems	Li <i>et al.</i> (2019)
Dry-seeded rice (DSR) systems	Integration of hand weeding with a post-emergence application of bispyribac sodium	Awan <i>et al.</i> (2019)
Herbicide OnDuty	(imazapic + imazapyr)	Mardiana-Jansar <i>et al.</i> (2019)
Coupled cropping-breeding modes	Integrated rice-duck farming	Wei <i>et al.</i> (2019)
Bioherbicide	Jellyfish chips and rice bran	Sugimoto <i>et al.</i> (2019)
Organic farming	<i>Ampullaria tischbeini</i> (Dohrn) snail	Jong-Song <i>et al.</i> (2018)
Mulching	Polythene mulching	Ratnayake <i>et al.</i> (2018)
Mechanical weed control	Hand weeding	Muhammad <i>et al.</i> (2016)
Biological method	Phytotoxins	Khanh <i>et al.</i> (2007)
Allelopathic potential of plant	<i>Tagetes minuta</i>	Batish <i>et al.</i> (2007)
Allelopathic potential of plant	Dwarf lilyturf (<i>Ophiopogon japonicus</i> Ker-Gawl)	Lin <i>et al.</i> (2004)

5. Conclusion and recommendations

This review highlights several weed management techniques that have been used in the rice fields. Previous literature studies have shown that it is beneficial to use biological-based method as opposed to the use of herbicide to control weed growth. The use of herbicides is laborious, costly, time consuming, and harmful to the soil as well as the environment. Furthermore, the excessive use of herbicides and pesticides in the agricultural industry has resulted in a significant decrease in biodiversity with adverse environmental effects on paddy fields and rice production (Li *et al.*, 2019; Mardiana-Jansar *et al.* 2019; Rueda-Ayala *et al.*, 2020). We believe that an integrated approach, including knowledge and adequate management can promote to the creation of new weed control strategies in rice cultivation.

Comprehensive studies should be performed to investigate the use of low-cost, integrated weed management technologies involving the stale seedbed technique, appropriate aerobic rice genotypes, various cultural, mechanical, and physical methods as well as the use of low dose herbicides for diverse ecosystems in various regions. It is proposed that the combination of graminicides and one type of herbicide for different weed species should be employed due to the presence of diverse weed populations in the paddy field. This method is thought to exert an additive, broad-spectrum effect on weed control to obtain better yields. Additionally, integrated weed control and management program using low quantities of herbicides and cultural practices to protect the environment and reduce herbicide resistance are recommended for future studies. Moreover, the knowledge and understanding of weed biology will be useful for the improvement of weed management strategies.

Acknowledgments

We would like to express our very great appreciation to University PGRI Yogyakarta, Indonesia and University Pendidikan Sultan Idris, Malaysia for helping in preparing this manuscript.

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